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Final Report for Period 10/1/90 - 1/30/94

This document is a final report on research activities and accomplishments that occurred during the funding period of 10-1-90 through 1-30-94. The focus of our interdisciplinary investigation during the Dynamics Explorer Mission was on the complex coupling processes that tap the magnetio-storm energy, stored in the ring current particle reservoir, and transport this energy into the subauroral, midlatitude and even equatorial ionospheric regions. The transport of energy through the inner magnetosphere and into the underlying ionospheric regions is a critical element in our understanding of the impact of solar and magnetic disturbances on upper atmospheric and ionospheric regions equatorward of the auroral zone.

Major Scientific Accomplishments Fully or Partially Supported Under Grant #NAG 5-472.

The Dynamics Explorer mission, with its two satellites in coplanar polar orbit, was uniquely configured to carry out investigations of the processes that transport energy from the source region in the inner magnetosphere (observed by DE-1) into the underlying ionosphere (observed nearly simultaneously by DE-2). Over the final three year period of the recently completed investigation, significant advances were made using a newly developed large-scale ring current-atmosphere interaction model (RAM), in concert with related theoretical and observational studies. Observations by the DE spacecraft pair were combined with ground-based photometric observations as well as with measurements by other satellites orbiting in the inner magnetosphere. Highlights include the simulation of the ~10 hour lifetime of a SAR arc, the discovery of a two-stage ion heating process, and the simulated build-up of suprathermal ion populations in the outer plasmasphere from a ring current source population. An interesting and previously unknown connection was found between ring current nose events and intensifications of SAR arc emissions in the storm main phase. Resonant interactions between ring current protons ($E > 80$ keV) and ducted plasmaspheric hiss were shown capable of driving energy diffusion near the edge of the atmospheric loss cone on time scales comparable to other ring current loss processes. The following paragraphs will give some background information and then present details of these and other exciting experimental and theoretical results.

Role of Ring Current O^+ in the Energetics of the Subauroral Ionosphere

The energy contained in the ring current populations is transferred to the thermal populations of the plasmasphere and the underlying ionosphere as the ring current decays. Each of the major ring current loss processes are dependent on the composition and energy characteristics of the ring current, which are highly variable. This results in a dynamical interaction. Our group has helped define the impact of these changing characteristics on the Coulomb interaction. During the recovery phase of magnetic storms, we demonstrated, using DE data, that the O^+ component of the ring current is a major source of thermal electron heating [Fok et al., 1991a; Fok et al., 1991b; Kozyra et al., 1987; Kozyra et al., 1990]. This is true in spite of the fact that O^+ is generally a

minor species in the ring current [Gloeckler and Hamilton, 1987]. The importance of the O^+ component over that of the other ring current components in the transfer of energy to the thermal plasma results from the energy dependent nature of the Coulomb interaction. The energy loss of a ring current ion traveling through a thermal electron plasma (and the corresponding energy gained by the thermal plasma) maximizes for ring current ions whose velocity approaches the thermal electron velocity (see Kozyra *et al.* [1987]). For a distribution of ring current ions moving through the ~ 1 eV thermal electron plasma in the outer plasmasphere, this condition is met and maximum energy loss per unit time occurs for ~ 32 keV O^+ ions, ~ 8 keV He^+ ions and ~ 2 keV H^+ ions. The ring current flux distribution maximizes near 40-60 keV during a moderate magnetic storm and drops off dramatically both at higher and lower energies. The 40-60 keV peak in the ring current flux occurs at energies where an efficient energy transfer is possible between thermal electrons and ring current O^+ , but where relatively little energy is transferred from the H^+ and He^+ components. As a result, ring current O^+ is a major ring current energy source for the thermal plasma during the storm recovery phase.

Solar Cycle and Seasonal Variations in the Ring Current Energy Source & Corresponding Ionospheric Signatures

The ring current energy source produces dramatic signatures in the subauroral ionosphere. As stated earlier, the Dynamics Explorer mission was specifically designed to observe both the energy source region and its effects in the underlying ionosphere and thus was well suited to carry out investigations of the processes coupling these regions. Energy, transferred between ring current particles and thermal electrons in the outer plasmasphere, reaches the ionosphere via a very low-energy electron flux (~ 1 eV) and/or heat conduction and results in elevated subauroral electron temperatures. This enhancement in the electron temperature, called the subauroral electron temperature peak, is a characteristic feature of the subauroral ionosphere [Kozyra *et al.*, 1986]. The variations of the subauroral electron temperature peak with solar cycle and season have been examined by Fok *et al.*, [1991a; 1991b] and are consistent with a ring current O^+ energy source.

If the subauroral Te peak is the energetic signatures of the thermal electron heating by the ring current, Stable Auroral Red (SAR) arc emissions are the optical signature. SAR arc emissions originate from the relaxation of oxygen atoms left in the 1D state after collisions with thermal electrons in the high energy ($E > 1.96$ eV) tail of the thermal electron distribution. Emissions are nonlinearly dependent on the electron temperature and nearly monochromatic. Column 630 nm intensities of hundreds of Rayleighs (R) are usual during magnetically disturbed periods and can reach values of many kR's. Observations of SAR arc intensities over a full solar cycle [Slater and Kleckner, 1989] indicate that, though there is a tendency for intensities to increase with Dst (total kinetic energy of the ring current), weak SAR arcs occur during all levels of magnetic activity and, in fact, maximum intensities appear to be associated with moderate magnetic storms. In addition, SAR arcs are weaker at solar minimum than at solar maximum for comparable magnetic storms (as indicated by Dst). This implies that the "efficiency" of the energy transfer between the ring current and thermal plasma decreases with the solar cycle. In other words, for a given total ring current energy content, more of the ring current energy is lost to Coulomb drag during solar maximum than during solar minimum conditions.

This is also consistent with ring current O^+ as an energy source. At solar maximum, a larger percentage of the ring current ion population is O^+ and thus a larger portion of the

total ring current energy is lost to thermal electron heating. The interesting tendency for weak SAR arcs to occur during all levels of magnetic activity has yet to be explained. The increase of the O^+ content of the ring current with magnetic activity would imply a corresponding increase in SAR arc intensity. The increase in the characteristic energy of the ring current with increasing magnetic activity and rapid precipitation loss of ring current O^+ in large storms have important impacts on the relationship between SAR arc intensity and the level of magnetic activity.

Strong Coupling Between the Ionosphere and Inner Magnetosphere

Another very interesting implication of statistical studies of the subauroral Te peak and accompanying SAR arc emissions, performed with partial funding under this grant, is that the heating of the thermal plasma is, in a sense, self-regulating [Fok et al., 1991a; Fok et al., 1991b; Kozyra et al., 1990]. Sources and sinks of energy in the thermal plasma vary over orders of magnitude with solar activity, but are each in phase with the ionospheric density variations, maintaining a fairly constant electron temperature for a fixed magnetic activity level. The reason for this is as follows. Ionospheric outflows provide heavy ions to the ring current region [Chappell, 1988]. The magnitude of these outflows depends on the ionospheric densities. The ring current energy source for the thermal plasma, which varies as the oxygen ion content of the ring current, is thus directly related to the ionospheric densities through these outflows. The magnitude of the electron temperature established in the ionosphere, in response to a given energy source, depends both on the magnitude of the energy source and on the strength of the ionospheric cooling, which is also proportional to the ionospheric density. Therefore the sources and sinks of plasma energy vary in phase with solar activity. The sources and sinks, however, do not vary in an identical manner with magnetic activity. Statistical studies indicate a general increase in the electron temperature with magnetic activity though a very large statistical variation about this trend exists [Fok et al., 1991b; Kozyra et al., 1986]. The manner in which the sources and sinks of thermal plasma heating vary with magnetic activity in the subauroral region is still only understood in a qualitative sense.

Most Recent Scientific Results

During the last year of the 1990-1993 period, significant progress was made on a number of fronts with full or partial support of this grant. Our coordinated program of observational and theoretical studies of energy transfer and coupling processes included: (1) a large-scale simulation of the ring current-plasmasphere interaction from which important new insights on thermal ion and electron heating as well as suprathermal populations emerged, (2) a study of the role of ring current nose events in SAR-arc intensifications during the main phase of a magnetic storm which provides a potential low-altitude optical signature of early ring current formation, (3) an investigation of the effects of resonant interaction between protons and ducted plasmaspheric hiss on the ring current proton distribution, which provides a potential explanation for the characteristic regions of anisotropic proton precipitation in the subauroral ionosphere and (4) an observational study of large-scale ducts in the outer plasmasphere. A short summary of the most important results from these most recent studies is presented below.

(1) Large Scale Simulation of the Ring Current - Plasmasphere Interaction

A ring current - atmosphere interaction model (RAM) has been developed that traces the evolution of the ring current in the equatorial plane during magnetic storm recovery phase and calculates the heating of the thermal plasma resulting from the ring current decay. Electron heating rates reach values sufficient to support a SAR-arc with an intensity of

several 100 R, with a lifetime of some 10 hours. This predicted magnitude and lifetime of the SAR arc is consistent with observational information. An important new coupling process has been revealed by these RAM calculations. A lower energy (10's of eV to keV) ion population builds up during the recovery phase as the higher energy (~10's - 100's of keV) ring current ion population degrades in energy during Coulomb collisions with plasmaspheric electrons. The global features of the build-up and the decay of suprathermal ions are presented in *Fok et al.*, [1993]. The temporal history of the suprathermal population depends both on the species and on the characteristic energy of the parent ring current population. Suprathermal O⁺ ions build up with the longest characteristic time scale. Significant suprathermal O⁺ is still present a full 2 days into the recovery phase of the storm. A suprathermal ion population with characteristics similar to the suprathermal distributions predicted by the model, for moderate storm conditions, has been observed [*Lennartsson and Sharp*, 1982; *Shelley et al.*, 1985], but has not been previously attributed to a ring current decay source.

The suprathermal ion population, discussed above, is of sufficiently low energy that Coulomb collisions with thermal ions in the outer plasmasphere begin to claim an increasing share of the energy loss; for higher energy ring current ions energy loss to the plasmaspheric electrons dominates. It is worth noting that the peak ion energy deposition rates are more than an order of magnitude less than the peak electron energy deposition rates. There are, however, significant differences in thermal conductivity between the ions and electrons. The thermal electron conductivity greatly exceeds that of the ions; therefore, a large portion of the energy deposited in the electrons is conducted to the underlying ionosphere whereas the energy deposited in the ions remains largely in the outer plasmasphere. The difference in conductivity in the ion compared to the electron gas means that more than an order of magnitude less energy deposited in the ions at high altitudes may still result in higher ion than electron temperatures in the outer plasmasphere; the electrons will be hotter than the ions in the underlying ionosphere (c.f., *Chandler et al.* [1988]). The ion heating rate is sufficient to support ~5000 °K ion temperatures in the outer plasmasphere and has a very different temporal history than the electron heating rates derived from ring current Coulomb drag energy loss. In summary, the RAM model predicts that thermal ion heating by the ring current ions is a two-stage process; a low-energy ion population is first formed as a result of Coulomb collisions with plasmaspheric electrons and then this population transfers an increasing fraction of its energy to the thermal ions as it degrades further in energy. At the present time, it appears that the relationship between enhanced ion temperatures and magnetic activity is a complex one; no clear understanding of the variation of ion temperatures with increasing magnetic activity has yet been achieved. The temporal evolution of the ion heating, in this scenario, is a complicated function of the history of the ring current ion decay and is not simply related to Dst or other global magnetic activity indices. In addition, the heating of the thermal electrons and ions by the ring current as a result of Coulomb collisions leads to hotter ion than electron temperatures in the outer plasmasphere and a very different temporal history for thermal ion and thermal electron heating during the recovery phase of a magnetic storm.

The results of our ring current drift/loss model have been presented at the 1992 Spring AGU meeting [*Fok et al.*, 1992], the 1992 Cambridge Workshop in Theoretical Geoplasma Physics [*Kozyra*, 1992b], the 1992 COSPAR meeting [*Kozyra*, 1992a], the 1992 Huntsville Workshop on Magnetosphere/Ionosphere Plasma Models [*Fok et al.*, 1992] and the 1993 IAGA meeting [*Kozyra et al.*, 1993]. A review article based on these presentations was prepared for the Cambridge conference proceedings [*Kozyra*, 1993]. Details of the model are given in *Fok* [1993] and *Fok et al.* [1993].

(2) The Role of Ring Current Nose Events in SAR-arc Intensifications

An examination of stable auroral red (SAR) arc emissions over the last solar cycle [Slater and Kleckner, 1989] indicates that the strongest emissions, during the lifetime of a particular SAR arc, sometimes occur in association with the main phase of the magnetic storm. A previous study by Kozyra *et al.*, [1987] demonstrated that a dominant energy source for these emissions derives from the O^+ component of the ring current. The O^+ content of the ring current increases with increasing magnetic activity reaching its maximum percentage contribution near minimum Dst for a particular storm. This variation in the O^+ content of the ring current is inconsistent with an early main phase enhancement of SAR arc emissions since this enhancement occurs before the O^+ percentage has maximized. In order to investigate the source of main phase enhancements in SAR arc emissions, a study of the September 19-24, 1984 magnetic storm period was carried out. The emissions associated with the main phase of this storm (~ 400 R) were an order of magnitude greater than those associated with the recovery phase (10's of R). Energetic particle measurements from the DE-1 and AMPTE spacecraft, on field lines that map to the SAR arc position at low altitude, revealed that an enhancement of the 15-25 keV H^+ component of the ring current, during the main phase of this magnetic storm, was responsible for an approximately order of magnitude increase in the electron heating rate and SAR arc emissions during the main phase compared to the recovery phase. In agreement with previous work, ring current O^+ supplied the bulk of the electron heating during storm recovery phase. The early main phase enhancement in this relatively low-energy H^+ flux occurred in association with a ring current "nose event", a front of ions injected into the inner magnetosphere in response to a discontinuous change in the cross-tail electric field (c.f., Ejiri *et al.* [1980]). The association between nose events and intensifications of SAR arc emissions in the main phase has not previously been explored, but is a natural consequence of the injection of significant fluxes of relatively low energy ring current ions earthward of the plasmapause during early storm-time ring current formation. These observations raise the interesting possibility that information regarding early ring current development might be extracted from SAR-arc intensifications during the storm main phase, observed by ground-based optical instruments.

(3) Anisotropic Proton Precipitation in the Subauroral Region

Dynamics Explorer -1 particle and field data indicate that large-scale regions of ducted plasmaspheric hiss are present in the outer plasmasphere in association with large-scale thermal density structures [Kozyra *et al.*, 1992; Kozyra *et al.*, 1987]. Small wave normal angles are maintained in the ducting process, therefore waves can resonate with protons at ring current energies and produce changes in the ring current distribution. A calculation of quasi-linear, bounce-averaged diffusion coefficients was made for protons interacting with a ducted plasmaspheric hiss band, having the characteristics observed by the Plasma Wave Instrument (PWI) on DE-1, with the following results: (1) high order ($n=\pm 100$) harmonic interactions make important contributions to the diffusion, (2) positive and negative harmonics are both equally important, (3) energy and pitch-angle diffusion are of comparable magnitudes, (4) the interaction cannot be represented as unmagnetized if diffusion into the loss cone is considered, and (5) diffusion time scales are of the order of 1-100 days and are comparable to other loss processes for protons at energies > 80 keV. These results were recently published [Kozyra *et al.*, 1994].

The bounce-averaged diffusion coefficients described above were used in a numerical solution of the Fokker-Planck equation describing the diffusion of ring current protons during interactions with a specified distribution of ducted plasmaspheric hiss. Energy diffusion was very important at moderate pitch angles. On a time scale of the order of 10's of days the flux at moderate pitch angles increased by an order of magnitude causing an enhancement of the distribution function at pitch angles near the edge of the atmospheric loss cone. Observations of anisotropic proton distributions in the outer plasmasphere were made on low-altitude spacecraft (~400-800 km) that showed increases in locally-mirroring protons [Lundblad and Soraas, 1978] in agreement with the simulation. Time scales are comparable to charge-exchange and Coulomb loss lifetimes for protons at energies above ~80 keV. The results of this study was presented at the Fall 1992 AGU meeting [Rasmussen *et al.*, 1992]; a paper is in preparation.

(4) Characterization of Large-Scale Wave Ducts in the Outer Plasmasphere

Large-scale ducts in the outer plasmasphere have not previously been characterized with regards to their temporal evolution and occurrence statistics, the intensity of the associated ducted emissions, and coincident particle signatures. In addition, never before have low altitude signatures of these ducts been systematically examined. The DE satellite pair are uniquely suited to provide this information. An interest in these observations stems from the potential importance of large-scale ducts in the outer plasmasphere in understanding the processes responsible for the growth and maintenance of plasmaspheric hiss as well as from the impact of the ducted waves on ion energy loss from the ring current. A half dozen case studies were selected during which nearly simultaneous DE-1 and DE-2 observations were available on field lines threading the large-scale duct structures. A data set is being accumulated containing observations from particle and wave instruments on DE-1 and -2. First results were presented at the 1992 Fall AGU meeting [Kozyra *et al.*, 1992]. Further work in this area continues with funding from other sources.

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